Forest Carbon Assessment for the Wallowa-Whitman National Forest in the Forest Service's Pacific Northwest Region

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1.0 Introduction

Carbon uptake and storage are some of the many ecosystem services provided by forests and grasslands. Through the process of photosynthesis, growing plants remove carbon dioxide (CO_2) from the atmosphere and store it in forest biomass (plant stems, branches, foliage, roots) and much of this organic material is eventually stored in forest soils. This uptake and storage of carbon from the atmosphere helps modulate greenhouse gas (GHG) concentrations in the atmosphere. Estimates of net annual storage of carbon indicate that forests in the United States (U.S.) constitute an important carbon sink, removing more carbon from the atmosphere than they are emitting (Pan *et al.*, 2011a). Forests in the U.S. remove the equivalent of about 12 percent of annual U.S. fossil fuel emissions or about 206 teragrams of carbon after accounting for natural emissions, such as wildfire and decomposition (US EPA, 2015; Hayes *et al.*, 2018).

Forests are dynamic systems that naturally undergo fluctuations in carbon storage and emissions as forests establish and grow, die with age or disturbances, and re-establish and regrow. When trees and other vegetation die, either through natural aging and competition processes or disturbance events (e.g., fires, insects), carbon is transferred from living carbon pools to dead pools, which also release carbon dioxide through decomposition or combustion (fires). Management activities include timber harvests, thinning, and fuel reduction treatments that remove carbon from the forest and transfer a portion to wood products. Carbon can then be stored in commodities (e.g., paper, lumber) for a variable duration ranging from days to many decades or even centuries. In the absence of commercial thinnings, harvests, and fuel reduction treatments, forests will thin naturally from mortality-inducing disturbances or aging, resulting in dead trees decaying and emitting carbon to the atmosphere.

Following natural disturbances or harvests, forests regrow, resulting in the uptake and storage of carbon from the atmosphere. Over the long term, forests regrow and often accumulate the same amount of carbon that was emitted from disturbance or mortality (McKinley *et al.*, 2011). Although disturbances, forest aging, and management are often the primary drivers of forest carbon dynamics in some ecosystems, environmental factors such as atmospheric CO_2 concentrations, climatic variability, and the availability of limiting forest nutrients, such as nitrogen, can also influence forest growth and carbon dynamics (Caspersen *et al.*, 2000; Pan *et al.*, 2009).

Box 1. Description of the primary forest carbon models used to conduct this carbon assessment

Carbon Calculation Tool (CCT)

Estimates annual carbon stocks and stock change from 1990 to 2013 by summarizing data from two or more Forest Inventory and Analysis (FIA) survey years. CCT relies on allometric models to convert tree measurements to biomass and carbon.

Forest Carbon Management Framework (ForCaMF)

Integrates FIA data, Landsat-derived maps of disturbance type and severity, and an empirical forest dynamics model, the Forest Vegetation Simulator, to assess the relative impacts of disturbances (harvests, insects, fire, abiotic, disease). ForCaMF estimates how much more carbon (non-soil) would be on each national forest if disturbances from 1990 to 2011 had not occurred.

Integrated Terrestrial Ecosystem Carbon (InTEC) model

A process-based model that integrates FIA data, Landsat-derived disturbance maps, as well as measurements of climate variables, nitrogen deposition, and atmospheric CO_2. InTEC estimates the relative effects of aging, disturbance, regrowth, and other factors including climate, CO_2 fertilization, and nitrogen deposition on carbon accumulation from 1950 to 2011. Carbon stock and stock change estimates reported by InTEC are likely to differ from those reported by CCT because of the different data inputs and modeling processes.

The Intergovernmental Panel on Climate Change (IPCC) has summarized the contributions of global human activity sectors to climate change in its Fifth Assessment Report (IPCC, 2014). From 2000 to 2009, forestry and other land uses contributed just 12 percent of human-caused global CO_2 emissions.[1] The forestry sector contribution to GHG emissions has declined over the last decade (FAOSTAT, 2013; IPCC, 2014; Smith *et al.*, 2014). Globally, the largest source of GHG emissions in the forestry sector is deforestation (Pan *et al.*, 2011a; Houghton *et al.*, 2012; IPCC, 2014), defined as the removal of all trees to convert forested land to other land uses that either do not support trees or allow trees to regrow for an indefinite period (IPCC, 2000). However, the United States is experiencing a net increase in forestland in recent decades because of the reversion of agricultural lands back to forest and regrowth of cut forests (Birdsey *et al.*, 2006), a trend expected to continue for at least another decade (Wear *et al.*, 2013; USDA Forest Service, 2016).

In this section, we provide an assessment of the amount of carbon stored on the Wallowa-Whitman National Forest (NF) and how disturbances, management, and environmental factors have influenced carbon storage overtime. This assessment primarily used two recent U.S. Forest Service reports: the Baseline Report (USDA Forest Service, 2015) and Disturbance Report (Birdsey *et al.*, 2019). Both reports relied on Forest Inventory and Analysis (FIA) and several validated, data-driven modeling tools to provide nationally consistent evaluations of forest carbon trends across the National Forest System (NFS). The Baseline Report applies the Carbon

[1] Fluxes from forestry and other land use (FOLU) activities are dominated by CO_2 emissions. Non-CO_2 greenhouse gas emissions from FOLU are small and mostly due to peat degradation releasing methane and were not included in this estimate.

Calculation Tool (CCT) (Smith *et al.*, 2007), which summarizes available FIA data across multiple survey years to estimate forest carbon stocks and changes in stocks at the scale of the national forest from 1990 to 2013. The Baseline Report also provides information on carbon storage in harvested wood products (HWP) for each Forest Service region. The Disturbance Report provides a national forest-scale evaluation of the influences of disturbances and management activities, using the Forest Carbon Management Framework (ForCaMF) (Healey *et al.*, 2014; Raymond *et al.*, 2015; Healey *et al.*, 2016). This report also contains estimates of the long-term relative effects of disturbance and non-disturbance factors on carbon stock change and accumulation, using the Integrated Terrestrial Ecosystem Carbon (InTEC) model (Chen *et al.*, 2000; Zhang *et al.*, 2012). See Box 1 for descriptions of the carbon models used for these analyses. Additional reports, including the most recent Resource Planning Act (RPA) assessment (USDA Forest Service, 2016) and regional climate vulnerability assessments (Halofsky *et al.*, 2017) are used to help infer future forest carbon dynamics. Collectively, these reports incorporate advances in data and analytical methods, representing the best available science to provide comprehensive assessments of NFS carbon trends.

1.1 Background

The Wallowa-Whitman NF, located primarily in the northeastern corner of Oregon with parts stretching into Idaho and Washington, covers approximately 714,000 ha of forestland. Fir-spruce-mountain hemlock and douglas fir forest types are the most abundant across the Wallowa-Whitman NF, according to FIA data. The carbon legacy of Wallowa-Whitman NF and other national forests in the region is tied to the history of Euro-American settlement, land management, and disturbances. The first major influx of Euro-American settlers in the Pacific Northwest Region began in the mid-19th century, when some 53,000 settlers traveled to the region via the Oregon Trail. The rise of the lumber industry in this region was driven by the California Gold Rush and the development of booming cities such as San Francisco. The construction of transcontinental railroads in the 1880s accelerated the growth of the logging industry, bringing with it a new influx of settlers and the opportunity for efficient export of wood products to other parts of the country that had been overharvested. As settlements in the region expanded, they became a significant source of fire ignitions, prompting the implementation of fire suppression efforts around 1910. As technology advanced and timber outputs continued to increase, many began to fear that timber companies would deplete the supply of wood. Farmers were particularly concerned that a combination of

Box 2. Carbon Units. The following table provides a crosswalk among various metric measurements units used in the assessment of carbon stocks and emissions.

Tonnes				Grams		
Multiple	Name	Symbol		Multiple	Name	Symbol
				10^0	Gram	G
				10^3	kilogram	Kg
10^0	tonne	t		10^6	Megagram	Mg
10^3	kilotonne	Kt		10^9	Gigagram	Gg
10^6	Megatonne	Mt		10^{12}	Teragram	Tg
10^9	Gigatonne	Gt		10^{15}	Petagram	Pg
10^{12}	Teratonne	Tt		10^{18}	Exagrame	Eg
10^{15}	Petatonne	Pt		10^{21}	Zettagram	Zg
10^{18}	Exatonne	Et		10^{24}	yottagram	Yg

1 hectare (ha) = 0.01 km^2 = 2.471 acres = 0.00386 mi^2
1 Mg carbon = 1 tonne carbon = 1.1023 short tons (U.S.) carbon
1 General Sherman Sequoia tree = 1,200 Mg (tonnes) carbon
1 Mg carbon mass = 1 tonne carbon mass = 3.67 tonnes CO_2 mass
A typical passenger vehicle emits about 4.6 tonnes CO_2 a year

logging, forest fires, and overgrazing would destroy the forests that regulated the flow of streams on which they depended.

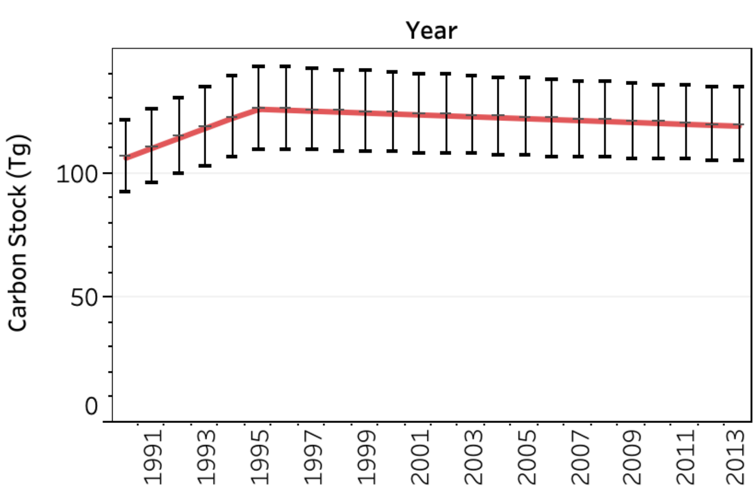
In the 1890s the Forest Reserves Act was passed, and President Cleveland set aside millions of acres of public forest in the region, largely to protect the watersheds they supported. This legacy of timber harvesting and fire suppression and exclusion efforts is visible today, influencing forest age structures, tree composition, and carbon dynamics (Hessburg *et al.*, 2005; Alig *et al.*, 2006). Since the 1990s, the rate of timber extraction from the Wallowa-Whitman NF has declined and new management practices have prioritized ecosystem resilience and the management of the remaining late successional, or old growth, forest stands across the Wallowa-Whitman NF (Halofsky et al. 2019). However, fires continue to be a management concern on the forest, which has experienced several significant fires since 2000. The frequency and severity of these disturbance events is projected to increase with warming temperatures (Halofsky et al. 2020).

2.0 Baseline Carbon Stocks and Flux

2.1 Forest Carbon Stocks and Stock Change

According to results of the Baseline Report (USDA Forest Service, 2015), carbon stocks in the Wallowa-Whitman NF increased from 106.2±14.2 teragrams of carbon (Tg C) in 1990 to 118.9±14.7 Tg C in 2013, a 12 percent increase in carbon stocks over this period (Fig. 1). For context, 118.9 Tg C is equivalent to the emissions from approximately 94.9 million passenger vehicles in a year. Despite some uncertainty in annual carbon stock estimates, it appears that carbon stocks in the Wallowa-Whitman have been relatively stable from 1990 to 2013 (Fig. 1).

Figure 1. *Total forest carbon stocks (Tg) from 1990 to 2013 for Wallowa-Whitman National Forest, bounded by 95 percent confidence intervals. Estimat*



About 57 percent of forest carbon stocks in the Wallowa-Whitman NF are stored in litter material on the forest floor and soil carbon contained in organic material to a depth of one meter (excluding roots). The aboveground portion of live trees, which includes all live woody vegetation at least one inch in diameter (Fig. 2) is the second largest carbon pool, storing another 26.5 percent of the forest carbon stocks. Recently, new methods for measuring soil carbon have found that the amount of carbon stored in soils generally exceeds the estimates derived from using the methods of the CCT model by roughly 12 percent across forests in the United States (Domke *et al.*, 2017).

The annual carbon stock change can be used to evaluate whether a forest is a carbon sink or source in a given year. Carbon stock change is typically reported from the perspective of the atmosphere. A negative value indicates a carbon sink: the forest is absorbing more carbon from the atmosphere (through growth) than it emits (via decomposition, removal, and combustion). A positive value indicates a source: the forest is emitting more carbon than it takes up.

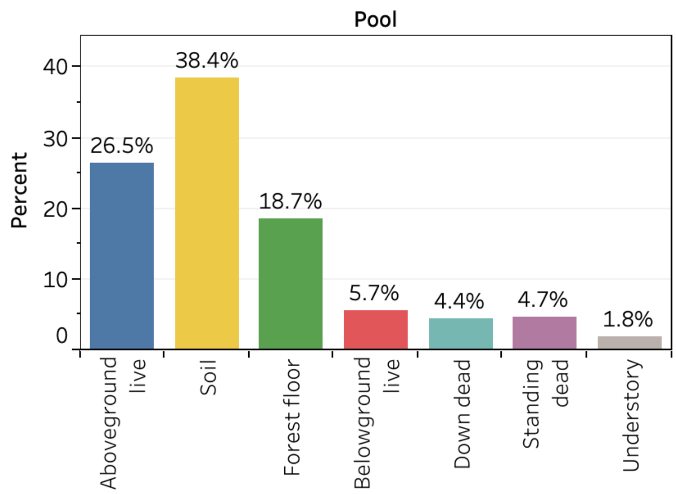


Figure 2. *Percentage of carbon stocks in 2013 in each of the forest carbon pools, for Wallowa-Whitman National Forest. Estimated using the CCT model.*

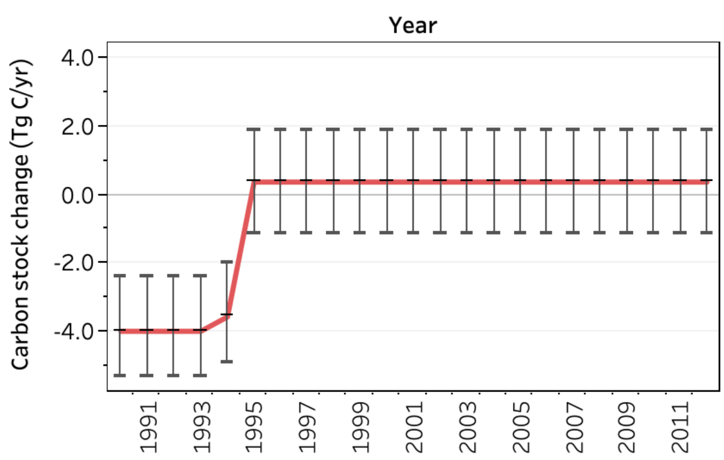


Figure 3. *Carbon stock change (Tg/yr) from 1990 to 2012 for Wallowa-Whitman National Forest, bounded by 95 percent confidence intervals. A positive value indicates a carbon source, and a negative value indicates a carbon sink. Estimated using the CCT model.*

Estimated annual carbon stock changes in the Wallowa-Whitman NF were -4.0 ± 1.4 Tg C per year (gain) in 1990 and 0.4 ± 1.5 Tg C per year in 2012 (loss) (Fig. 3). The uncertainty between annual estimates can make it difficult to determine whether the forest is a sink or a source in a specific year (i.e., uncertainty bounds overlap zero) (Fig. 3). However, the trend in carbon stock estimates from 1990 to 2013 (Fig. 1) over the 23-year period suggests that the Wallowa-Whitman NF carbon stocks are relatively stable and not an obvious source or sink.

Changes in forested area may affect whether forest carbon stocks are increasing or decreasing. The CCT estimates from the Baseline Report are based on FIA data, which may indicate changes in the total forested area from one year to the next. According to the FIA data used to develop these baseline estimates, the forested area in Wallowa-Whitman NF has increased from 642,090 ha in 1990 to 714,351 ha in 2013, a net change of 72,261 ha[2]. When forestland area increases, total ecosystem carbon stocks typically also increase, indicating a carbon sink. The CCT model used inventory data from two different databases. This may have led to inaccurate estimates of changes in forested area, potentially altering the conclusion regarding whether or not forest carbon stocks are increasing or decreasing, and therefore, whether the national forest is a carbon source or sink (Woodall *et al.*, 2011).

Carbon density, which is an estimate of forest carbon stocks per unit area, can help identify the effects of changing forested area. In the Wallowa-Whitman NF, carbon density has remained relatively stable with a from about 165.4 Megagrams of carbon (Mg C) per ha in 1990 to 166.5 Mg C per ha in 2013 (Fig. 4). The estimates of changes in carbon density across the period of record further suggests that total carbon stocks are relatively stable.

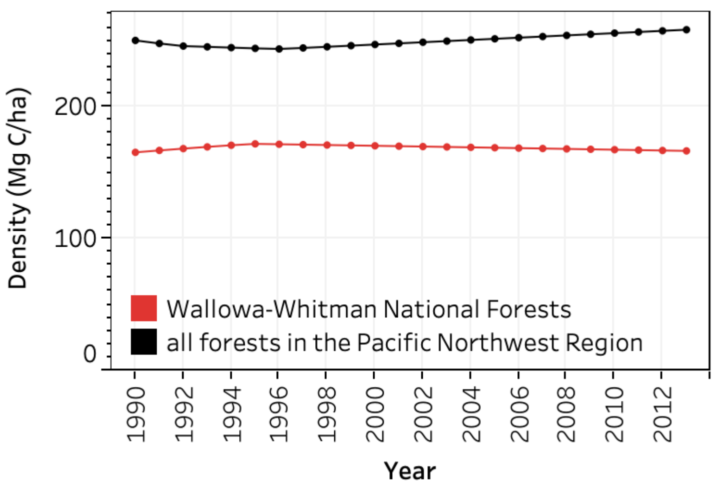


Figure 4. *Carbon stock density (Megagrams per hectare) in the Wallowa-Whitman National Forest and the average carbon stock density for all forests in the Pacific Northwest Region from 1990 to 2013. Estimated using CCT.*

Carbon density is also useful for comparing trends among units or ownerships with different forest areas. Unlike the Wallowa-Whitman NF, which has experienced relatively stable carbon densities from 1990 to 2013, most national forests in the Pacific Northwest Region have experienced increasing carbon densities over this period. Carbon density in the Wallowa-Whitman NF has been lower than the average for all national forest units in the Pacific Northwest Region (Fig.4). Differences in carbon density between units may be related to inherent differences in biophysical factors that influence growth and productivity, such as climatic conditions, elevation, and forest types. These differences may also be affected by disturbance and management regimes (see Section 3.0).

2.2 Uncertainty associated with baseline forest carbon estimates

All results reported in this assessment are estimates that are contingent on models, data inputs, assumptions, and uncertainties. Baseline estimates of total carbon stocks and carbon stock

[2] Forested area used in the CCT model may differ from more recent FIA estimates, as well as from the forested areas used in the other modeling tools.

change include 95 percent confidence intervals derived using Monte Carlo simulations[3] and shown by the error bars (Figs. 1, 3). These confidence intervals indicate that 19 times out of 20, the carbon stock or stock change for any given year will fall within error bounds. The uncertainties contained in the models, samples, and measurements can exceed 30 percent of the mean at the scale of a national forest, sometimes making it difficult to infer if or how carbon stocks are changing.

The baseline estimates that rely on FIA data include uncertainty associated with sampling error (e.g., area estimates are based on a network of plots, not a census), measurement error (e.g., species identification, data entry errors), and model error (e.g., associated with volume, biomass, and carbon equations, interpolation between sampling designs). As mentioned in Section 2.1, one such model error has resulted from a change in FIA sampling design, which led to an apparent change in forested area. Change in forested area may reflect an actual change in land use due to reforestation or deforestation. However, given that the Wallowa-Whitman NF have experienced minimal changes in land use or adjustments to the boundaries of the national forests in recent years, the change in forested area incorporated in CCT is more likely a data artefact of altered inventory design and protocols (Woodall *et al.*, 2013).

The inventory design changed from a periodic inventory, in which all plots were sampled in a single year to a standardized, national, annual inventory, in which a proportion of all plots is sampled every year. The older, periodic inventory was conducted differently across states and tended to focus on timberlands with high productivity. Any data gaps identified in the periodic surveys, which were conducted prior to the late 1990s, were filled by assigning average carbon densities calculated from the more complete, later inventories from the respective states (Woodall *et al.*, 2011). The definition of what constitutes forested land also changed between the periodic and annual inventory in some states, which may also have contributed to apparent changes in forested area.

In addition, carbon stock estimates contain sampling error associated with the cycle in which inventory plots are measured. Forest Inventory and Analysis plots are resampled about every 10 years in the Western United States, and a full cycle is completed when every plot is measured at least once. However, sampling is designed such that partial inventory cycles provide usable, unbiased samples annually but with higher errors. These baseline estimates may lack some temporal sensitivity, because plots are not resampled every year, and recent disturbances may not be incorporated in the estimates if the disturbed plots have not yet been sampled. For example, if a plot was measured in 2009 but was clear-cut in 2010, that harvest would not be detected in that plot until it was resampled in 2019. Therefore, effects of the harvest would show up in FIA/CCT estimates only gradually as affected plots are re-visited and the differences in carbon stocks are interpolated between survey years (Woodall *et al.*, 2013). In the interim, re-growth and other disturbances may mute the responsiveness of CCT to disturbance effects on carbon stocks. Although CCT is linked to a designed sample that allows straightforward error analysis, it is best suited for detecting broader and long-term trends, rather than annual stock changes due to

[3] A Monte Carlo simulation performs an error analysis by building models of possible results by substituting a range of values – a probability distribution – for any factor that has inherent uncertainty (e.g., data inputs). It then calculates results over and over, each time using a different set of random values for the probability functions.

individual disturbance events.

In contrast, the Disturbance Report (Section 3.0) integrates high-resolution, remotely-sensed disturbance data to capture effects of each disturbance event the year it occurred. This report identifies mechanisms that alter carbon stocks and provides information on finer temporal scales. Consequently, discrepancies in results may occur between the Baseline Report and the Disturbance Report (Dugan *et al.*, 2017).

2.3 Carbon in Harvested Wood Products

Although harvest transfers carbon out of the forest ecosystem, most of that carbon is not lost or emitted directly to the atmosphere. Rather, it can be stored in wood products for a variable duration depending on the commodity produced. Wood products can be used in place of other more emission intensive materials, like steel or concrete, and wood-based energy can displace fossil fuel energy, resulting in a substitution effect (Gustavsson *et al.*, 2006; Lippke *et al.*, 2011). Much of the harvested carbon that is initially transferred out of the forest can also be recovered with time as the affected area regrows.

Carbon accounting for harvested wood products (HWP) contained in the Baseline Report was conducted by incorporating data on harvests on national forests documented in cut-and-sold reports within a production accounting system (Smith *et al.*, 2006; Butler *et al.*, 2014). This approach tracks the entire cycle of carbon, from harvest to timber products to primary wood products to disposal. As more commodities are produced and remain in use, the amount of carbon stored in products increases. As more products are discarded, the carbon stored in solid waste disposal sites (landfills, dumps) increases. Products in solid waste disposal sites may continue to store carbon for many decades.

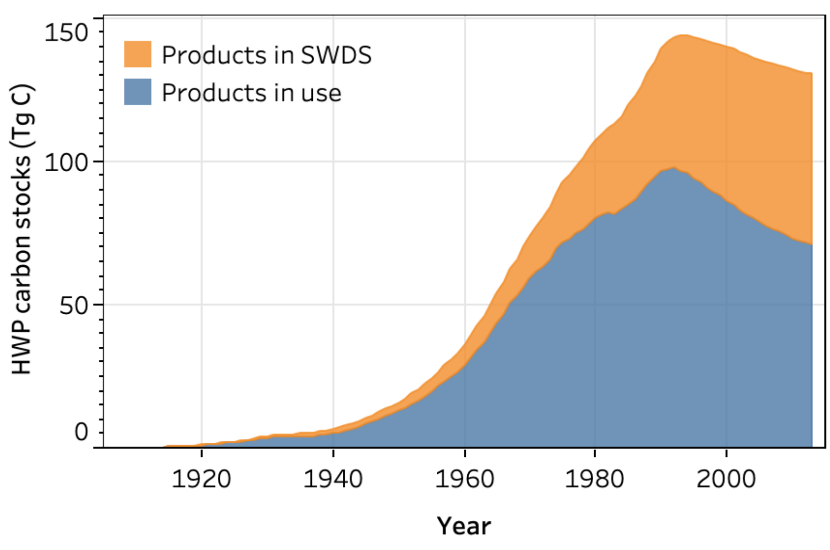


***Figure 5**. Cumulative total carbon (Tg) stored in harvested wood products (HWP) sourced from national forests in the Pacific Northwest Region . Carbon in HWP includes products that are still in use and carbon stored at solid waste disposal sites (SWDS). Estimated using the IPCC production accounting approach.*

In national forests in the Pacific Northwest Region, harvest levels remained low until they began to rise during World War II, which caused an increase in carbon storage in HWP (Fig. 5). Timber harvesting and subsequent carbon storage increased rapidly in the 1950s through 1970. Storage in products and landfills peaked at about 144 Tg C in 1994. However, because of a significant decline in timber harvesting in the late 1990s and early 2000s (to 1930s levels) carbon accumulation in products in use began to decrease to approximately 131 Tg by 2012. In the Pacific Northwest Region, the contribution of national forest timber harvests to the HWP carbon pool is less than the decay of retired products, causing a net decrease in product-sector carbon stocks. In 2013, the carbon stored in HWP was equivalent to approximately 5.3 percent of total forest carbon storage associated with national forests in the Pacific Northwest Region.

2.4 Uncertainty associated with estimates of carbon in harvested wood products

As with the baseline estimates of ecosystem carbon storage, the analysis of carbon storage in HWP also contains uncertainties. Sources of error that influence the amount of uncertainty in the estimates include: adjustment of historic harvests to modern national forest boundaries; factors used to convert the volume harvested to biomass; the proportion of harvested wood used for different commodities (e.g., paper products, saw logs); product decay rates; and the lack of distinction between methane and CO_2 emissions from landfills. The approach also does not consider the substitution of wood products for emission-intensive materials or the substitution of bioenergy for fossil fuel energy, which can be significant (Gustavsson *et al.*, 2006). The collective effect of uncertainty was assessed using a Monte Carlo approach. Results indicated a ±0.05 percent difference from the mean at the 90 percent confidence level for 2013, suggesting that uncertainty is relatively small at this regional scale (Butler *et al.*, 2014).

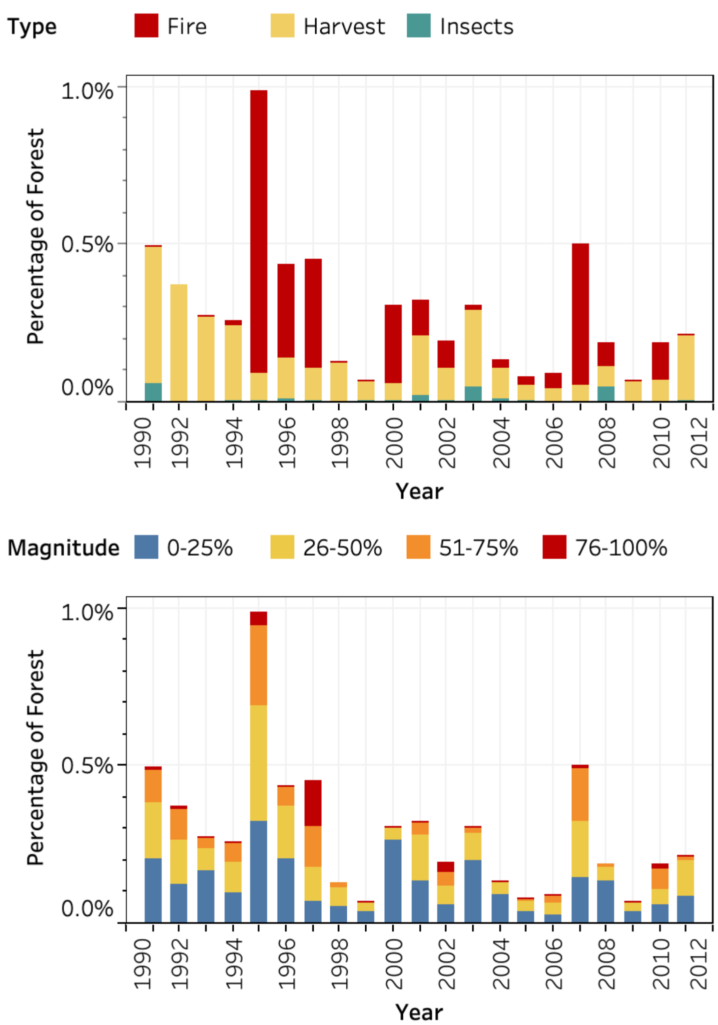


Figure 6. *Percentage of forest disturbed from 1990 to 2011 in Wallowa-Whitman National Forest by (a) disturbance type including fire, harvests, and insects,and (b) magnitude of disturbance (change in canopy cover). Estimated using annual disturbance maps derived from Landsat satellite imagery.*

3.0 Factors Influencing Forest Carbon

3.1 Effects of

Disturbance

The Disturbance Report builds on estimates in the Baseline Report by supplementing high-resolution, manually-verified, annual disturbance data from Landsat satellite imagery (Healey *et al.*, 2018). The Landsat imagery was used to detect land cover changes due to disturbances including fires, harvests, insects, and abiotic factors (e.g., wind, ice storms). The resulting disturbance maps indicate that timber harvest and fire have been the dominant disturbance types detected on the Wallowa-Whitman NF from 1990 to 2011, in terms of the total percentage of forested area disturbed over the period (Fig. 6a). However, according to the satellite imagery, timber harvests affected a relatively small area of the forest during this time. In most years, timber harvests affected less than 1 percent of the total forested area of the Wallowa-Whitman NF in any single year from 1990 to 2011. In total, harvest affected approximately 3.1 percent (approximately 21,888 ha) of the average forested area during this period (713,735 ha). Over the same period of time, fires affected approximately 2.8 percent of total forested area (19,661 ha). In general, the percentage of the forest harvested annually decreased over the 21-year period, whereas the occurrence and magnitude of fires varied annually, with notable fires taking place in 1995 and 2007 (Fig. 6). Lesser disturbance was due to insect activity (0.2 percent) during the 21-year period. The total amount of disturbed forest from all factors during this period was 6.1 percent, a total of 43,308 ha disturbed. Although disturbances varied in type and scale, they generally removed less than 50 percent of canopy cover (magnitude) on the forest (Fig. 6b, 6a). In total, only 1.5 percent of the forest had a disturbance that resulted in a canopy loss of greater than 50 percent from 1990 to 2012.

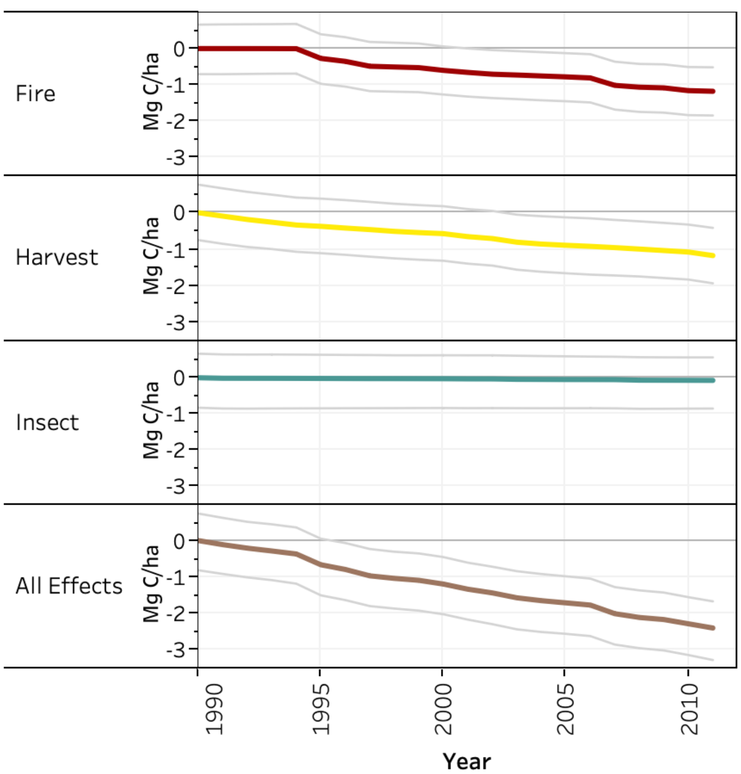


Figure 7. *Lost potential storage of carbon (Megagrams) as a result of disturbance for the period 1990-2011 in Wallowa-Whitman National Forest. The zero line represents a hypothetical undisturbed scenario. Gray lines indicate 95% confidence intervals. Estimated using the ForCaMF model.*

The Forest Carbon Management Framework (ForCaMF) incorporates Landsat disturbance maps summarized in Figure 6, along with FIA data in the Forest Vegetation Simulator (FVS) (Crookston & Dixon, 2005). The FVS is used to develop regionally representative carbon accumulation functions for each combination of forest type, initial carbon density, and disturbance type and severity (including undisturbed) (Raymond *et al.*, 2015). The ForCaMF model then compares the undisturbed scenario with the carbon dynamics associated with the historical disturbances to estimate how much more carbon would be on each national forest if the disturbances and harvests during 1990-2011 had not occurred. ForCaMF simulates the effects of disturbance and management only on non-soil carbon stocks (i.e., vegetation, dead wood, forest floor). Like CCT, ForCaMF results supply 95 percent confidence intervals around estimates derived from a Monte Carlo approach (Healey *et al.*, 2014).

Timber harvesting and fire in the Wallowa-Whitman NF were the primary disturbances

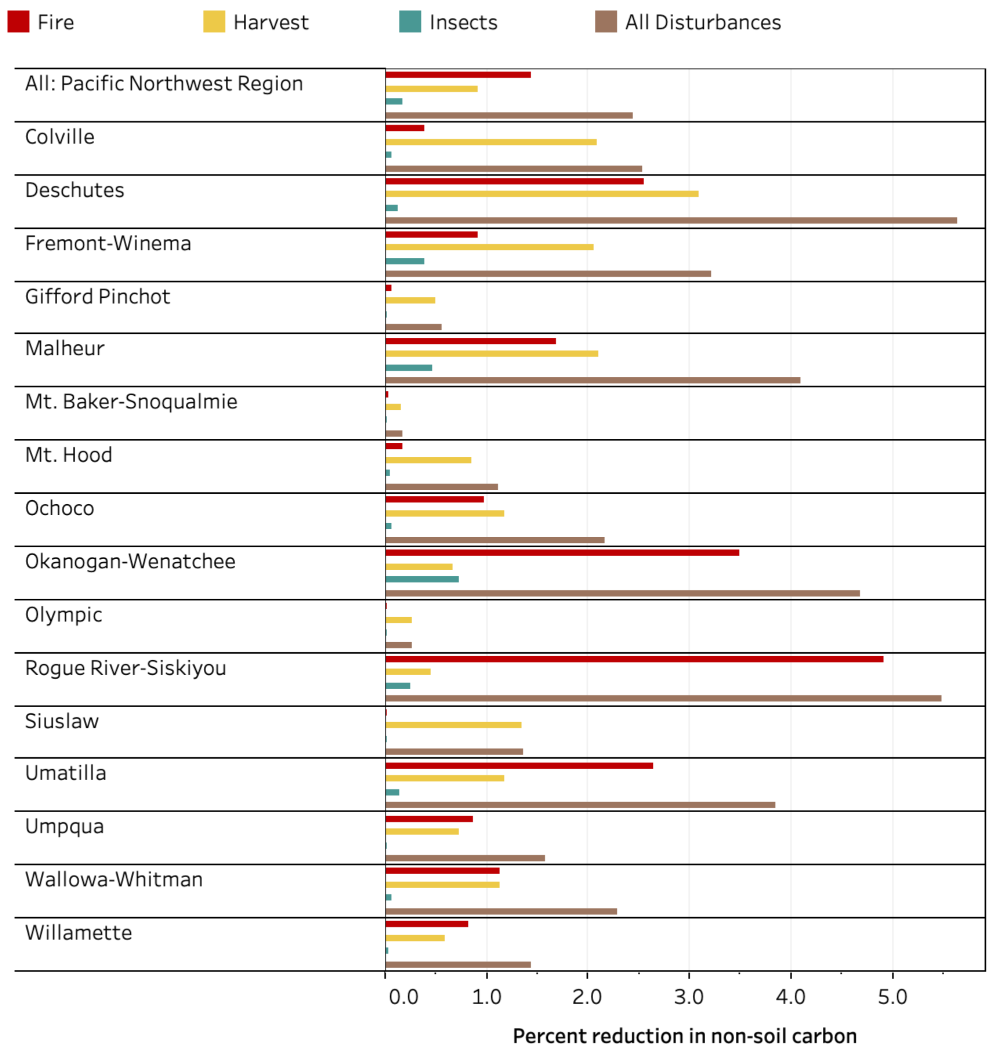


Figure 8. *The degrees to which 2011 carbon storage on each national forest in the Pacific Northwest Region was reduced by disturbance from 1990 to 2011 relative to a hypothetical baseline with no disturbance. The brown line indicates the effect of all disturbances types combined. Estimated using disturbance effects from ForCaMF and non-soil carbon stock estimates from CCT.*

influencing carbon stocks from 1990 to 2011 (Fig. 7). The ForCaMF model indicates that, by 2011, the Wallowa-Whitman NF contained 1.2 Mg C per ha less non-soil carbon (i.e., vegetation and associated pools) due to harvests since 1990, and 1.2 Mg C per ha less non-soil carbon due to fire since 1990, as compared to a hypothetical undisturbed scenario (Fig. 7). As a result, non-soil carbon stocks in the Wallowa-Whitman NF would have been approximately 2.2 percent higher in 2011 if harvests and fire had not occurred since 1990 (Fig. 8).

Across all national forests in the Pacific Northwest Region fire has been the most significant disturbance affecting carbon storage since 1990, causing non-soil forest ecosystem carbon stocks to be 1.4 percent lower by 2011 (Fig. 8). Considering all national forests in the Pacific Northwest Region, by 2011, harvesting accounted for the loss of 0.9 percent of non-soil carbon stocks. Insect activity accounted for a loss of only 0.2 percent if non-soil carbon stocks.

The ForCaMF analysis was conducted over a relatively short time. After a forest is harvested, it will eventually regrow and recover the carbon removed from the ecosystem in the harvest. However, several decades may be needed to recover the carbon removed depending on the type of the harvest (e.g., clear-cut versus partial cut), as well as the conditions prior the harvest (e.g., forest type and amount of carbon) (Raymond *et al*., 2015). The ForCaMF model also does not track carbon stored in harvested wood after it leaves the forest ecosystem. In some cases, removing carbon from forests for human use can result in lower net contributions of GHGs to the atmosphere than if the forest was not managed, when accounting for the carbon stored in wood products, substitution effects, and forest regrowth (Lippke *et al.*, 2011; McKinley *et al.*, 2011; Skog *et al.*, 2014; Dugan *et al.*, 2018). Therefore, the IPCC recognizes wood as a renewable resource that can provide a mitigation benefit to climate change (IPCC, 2000).

ForCaMF helps to identify the biggest local influences on continued carbon storage and puts the recent effects of those influences into perspective. Factors such as stand age, drought, and climate may affect overall carbon change in ways that are independent of disturbance trends. The purpose of the InTEC model was to reconcile recent disturbance impacts with these other factors.

3.2 Effects of Forest Aging

InTEC models the collective effects of forest disturbances and management, aging, mortality, and subsequent regrowth on carbon stocks from 1950 to 2011. The model uses inventory-derived maps of stand age, Landsat-derived disturbance maps (Fig. 6), and equations describing the relationship between net primary productivity (NPP) and stand age. Stand age serves as a proxy for past disturbances and management activities (Pan *et al.*, 2011b). In the model, when a forested stand is disturbed by a severe, stand-replacing event, the age of the stand resets to zero and the forest begins to regrow. Thus, peaks of stand establishment can indicate stand-replacing disturbance events that subsequently promoted regeneration.

Stand-age distribution for the Wallowa-Whitman NF derived from 2011 forest inventory data indicates elevated stand establishment from approximately 80-110 years ago, or 1900–1930 (Fig. 9a). This period of elevated stand regeneration came after intensive logging and fire suppression began in the early 1900s (Wallin et al., 1996). Policies focusing on restoring forests after decades of overharvesting and conversion of forest to agriculture enabled these stands to establish, survive, and accumulate carbon. Similar age trends have been widely observed in Pacific Northwest forests (Alig *et al.*, 2006). Stands regrow and recover at different rates depending on forest type and site conditions. Forests are generally most productive when they are young to middle age, then productivity peaks and declines or stabilizes as the forest canopy closes and as the stand experiences increased respiration and mortality of older trees (Pregitzer & Euskirchen, 2004; He *et al.*, 2012), as indicated by the in NPP-age curves (Fig. 9b), derived in part from FIA data.

InTEC model results show that Wallowa-Whitman NF was accumulating carbon steadily at the start of the analysis in the 1950s through the early-1980s (Fig. 10, positive slope of the orange line) as a result of regrowth following disturbances and heightened productivity of the young to middle-aged forests (30-60 years old) (Fig. 9b). As stand establishment declined and more stands reached slower growth stages around the mid-1980s, the rate of carbon accumulation declined (negative slope). This decrease in accumulated carbon is mainly driven by aging effects on forest stands.

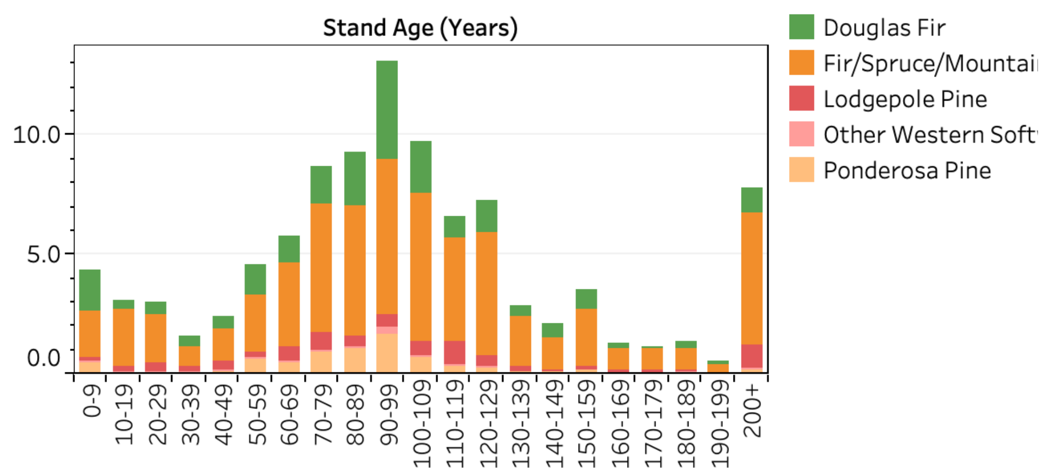


Figure 9. *(a) Stand age distribution in 2011 by forest type group in Wallowa-Whitman National Forest. Derived from forest inventory data.*

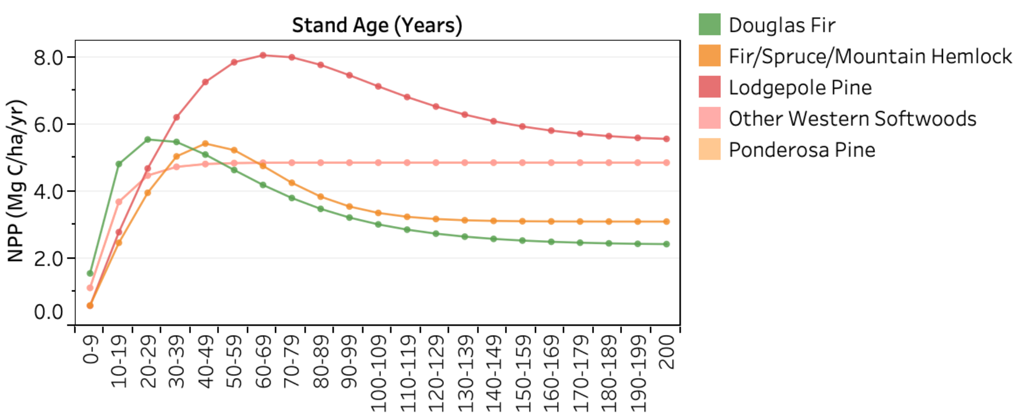


Figure 9. *(b) Net primary productivity-stand age curves by forest type group in Wallowa-Whitman National Forest. Derived from forest inventory data and He et al. 2012.*

3.3 Effects of Climate and Environment

The InTEC model also isolates the effects of climate (temperature and precipitation), atmospheric CO_2 concentrations, and nitrogen deposition on forest carbon stock change and accumulation. Generally annual precipitation and temperature conditions fluctuate considerably. The modeled effects of variability in temperature and precipitation on carbon stocks has varied from year-to-year. Overall, climatehas had a small negative effect on carbon stocks in the Wallowa-Whitman since the mid 1980s (Fig. 10). Warmer temperatures can increase forest carbon emissions through enhanced soil microbial activity and higher respiration (Ju *et al.*, 2007;

Melillo *et al.*, 2017), but warming temperatures can also reduce soil moisture through increased evapotranspiration, causing lower forest growth (Xu *et al.*, 2013).

In addition to climate, the availability of CO_2 and nitrogen can alter forest growth rates and subsequent carbon uptake and accumulation (Caspersen *et al.*, 2000; Pan *et al.*, 2009). Increased fossil fuel combustion, expansion of agriculture, and urbanization have caused a significant increase in both CO_2 and nitrogen emissions (Chen *et al.*, 2000; Keeling *et al.*, 2009; Zhang *et al.*, 2012). According to the InTEC model, higher CO_2 has consistently had a positive effect on carbon stocks in Wallowa-Whitman NF, tracking an increase in atmospheric CO_2 concentrations worldwide (Fig. 10). However, a precise quantification of the magnitude of this CO_2 effect on terrestrial carbon storage is one of the more uncertain factors in ecosystem modeling (Jones *et al.*, 2014; Zhang *et al.*, 2015). Long-term studies examining increased atmospheric CO_2 show that forests initially respond with higher productivity and growth, but the effect is greatly diminished or lost within 5 years in most forests (Zhu *et al.*, 2016). There has been considerable debate regarding the effects of elevated CO_2 on forest growth and biomass accumulation, thus warranting additional study (Körner *et al.*, 2005; Norby *et al.*, 2010; Zhu *et al.*, 2016).

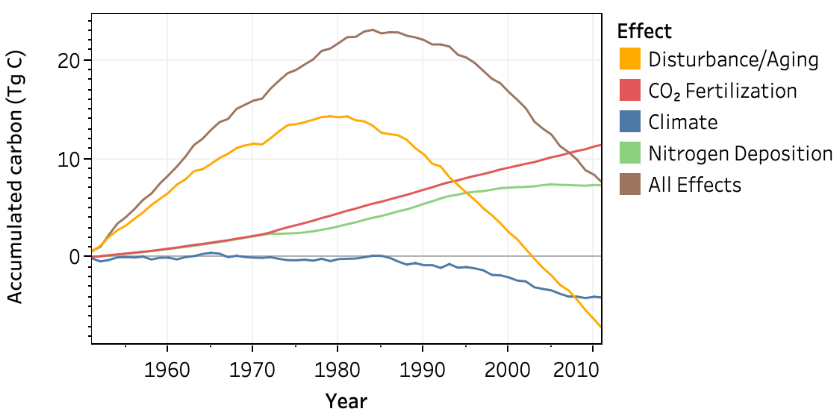


Figure 10. *Accumulated carbon in Wallowa-Whitman National Forest due to disturbance/aging, climate, nitrogen deposition, CO_2 fertilization, and all factors combined (shown in brown line) for1950–2011, excluding carbon accumulated pre-1950. Estimated using the InTEC model.*

Modeled estimates suggest that overall nitrogen deposition had a positive effect on carbon accumulation in the Wallowa-Whitman NF (Fig. 10). Like CO_2, the actual magnitude of this effect remains uncertain. A meta-analysis of nitrogen addition experiments and field observations estimates that nitrogen deposition enhances tree growth and increases global forest carbon uptake by 3-8% (de Vries et al., 2014). However, elevated nitrogen deposition can also decrease growth in some species for a variety of reasons, such as leaching of base cations in the soil, increased vulnerability to secondary stressors, and suppression by more competitive species (Pardo *et al.*, 2011). Some regional studies have documented negative effects on forest productivity associated with chronically high levels of nitrogen deposition in the western United States (Fenn *et al.*, 2003; Carter *et al.*, 2017; Pardo *et al.*, 2011). The InTEC model simulated that rates of carbon accumulation associated with nitrogen deposition decreased as deposition rates declined. Overall, the InTEC model suggests a net accumulation of carbon until the 1980s. By the mid-1980s, net combined effects of carbon accumulation declined on the forest and were partially offset by carbon accumulation from CO_2 fertilization and nitrogen deposition.

3.4 Uncertainty associated with disturbance effects and environmental factors

As with the baseline estimates, there is also uncertainty associated with estimates of the relative effects of disturbances, aging, and environmental factors on forest carbon trends. For example, omission, commission, and attribution errors may exist in the remotely-sensed disturbance maps used in the ForCaMF and InTEC models. However, these errors are not expected to be significant given that the maps were manually verified, rather than solely derived from automated methods. ForCaMF results may also incorporate errors from the inventory data and the FVS-derived carbon accumulation functions (Raymond *et al.*, 2015). To quantify uncertainties, the ForCaMF model employed a Monte Carlo-based approach to supply 95 percent confidence intervals around estimates (Healey *et al.*, 2014).

Uncertainty analyses such as the Monte Carlo are not commonly conducted for spatially explicit, process-based models like InTEC because of significant computational requirements. However, process-based models are known to have considerable uncertainty, particularly in the parameter values used to represent complex ecosystem processes (Zaehle *et al.*, 2005). InTEC is highly calibrated to FIA data and remotely-sensed observations of disturbance and productivity, so uncertainties in these datasets are also propagated into the InTEC estimates. National-scale sensitivity analyses of InTEC inputs and assumptions (Schimel *et al.*, 2015), as well as calibration with observational datasets (Zhang *et al.*, 2012) suggest that model results produce a reasonable range of estimates of the total effect (e.g., Fig. 10, “All effects”). However, the relative partitioning of the effects of disturbance and non-disturbance factors as well as uncertainties at finer scales (e.g., national forest scale) are likely to be considerably higher.

Results from the ForCaMF and InTEC models may differ substantially from baseline estimates (CCT), given the application of different datasets, modeling approaches, and parameters (Zhang *et al.*, 2012; Dugan *et al.*, 2017). The baseline estimates are almost entirely rooted in empirical forest inventory data, whereas ForCaMF and InTEC involve additional data inputs and modeling complexity beyond summarizing ground data.

3.5 Rangeland carbon

While there are many different definitions of rangelands, these ecosystems generally include natural grasslands, savannas, shrub lands, many deserts, tundras, alpine communities, marshes, or meadows (Reeves et al., 2018). The indigenous vegetation on these lands is predominately grasses, grass-like plants, forbs, or shrubs and is managed as a natural ecosystem. The Wallow-Whitman NF contains 226,911 hectares of rangelands accounting for approximately 23 percent of the total area on the Forest. Most of the carbon in these systems is found belowground in soils and roots (Derner and Schuman 2007; McKinley *et al.*, 2008; Janowiak *et al.*, 2017). By contrast, forests typically store roughly one-half of the total carbon belowground (Domke *et al.*, 2017). Soils generally provide a stable ecosystem carbon pool relative to other ecosystem carbon pools.

There are several drivers that can cause rangelands to gain or lose carbon. Many rangelands are highly influenced by fire and grazing, which temporarily remove above ground vegetation (Knapp *et al.*, 1998; Van Auken 2009). For example, altered wildfire regimes caused by fire suppression, overgrazing, and other factors is implicated in allowing many mesic and semi-arid grasslands in the United States to convert to shrublands (Van Auken 2009). Replacement of grassland with woody plants generally tends to increase total ecosystem carbon storage

(McKinley *et al.*, 2008; Li *et al.*, 2016; Abdallah *et al.* 2020). Conversely, some invasive species, such as *Bromus tectorum*, can reduce carbon in shrublands by propagating more intense fire that cause mortality of co-occurring woody species (Bradley *et al.*, 2006; Koteen *et al.*, 2012; Pilliod et al. 2017). The extent to which these opposing factors influence carbon dynamics in the rangelands on the Wallowa-Whitman NF is not well understood. However, these influences on total ecosystem carbon stocks on the entire Forest are likely small even considering any increasing woody plant encroachment and establishment of invasive species that has occurred over the last century.

The greatest lasting influence in rangeland ecosystem carbon stocks is land-use and land-cover change. For example, it is generally assumed that federal grassland areas have negligible changes in carbon due to limited land use and management change (Environmental Protection Agency, 2019). Because soil carbon in rangelands is generally stable, substantial changes in carbon pools and fluxes are typically a result of dramatic changes in land use or vegetation cover that persist indefinitely. For example, there can be substantial losses of soil carbon where rangelands have been converted to agricultural use (Derner and Schuman 2007). Like forests, managing the health of rangelands and avoiding land use and land cover change are key concerns for maintaining carbon stocks. Land-use change generally does not occur on the Wallowa-Whitman NF, although there is increasing development on private lands in the region.

Grazing has long played an important role in plant composition and nutrient cycling in many rangeland ecosystems extending from the Great Plains to the Pacific Northwest (Galbraith and Anderson, 1971; Knapp *et al.*, 1999). Large grazing ungulates, including domesticated livestock and bison, produce a variety of greenhouse gas (GHG) emissions. Livestock and wild ruminates produce methane from enteric fermentation, resulting from their digestive process. Nitrous oxide can be produced as a byproduct from soil microbial processes that chemically transform nitrogen in animal waste. The Environmental Protection Agency (2019) estimates that about 47 percent of the total GHG emissions in the agricultural sector are attributed to livestock. In turn, the agricultural sector contributes to about nine percent of total GHG emissions in the United States. The USDA's National Agricultural Statistics Service estimated in January 2019 that the United States had about 94.8 million cattle (NASS 2019). By comparison, as of 2019 the Wallowa-Whitman NF maintains grazing allotments for approximately 24,238 cattle and 3,369 sheep annually. However, many of these animals are not typically present on the Forest year-round.

4.0 Future Carbon Conditions

4.1 Prospective Forest Aging Effects

The retrospective analyses presented in the previous sections can provide an important basis for understanding how various factors may influence carbon storage in the future. For instance, the forests of the Wallowa-Whitman NF are mostly middle-aged and older (greater than 80 years);few stands are young (Fig. 9a). If the Forest continues on this aging trajectory, more stands will reach a slower growth stage in coming years and decades (Fig. 9b), potentially causing the rate carbon accumulation to decline and the forest may eventually transition to a steady state in the future. Although yield curves indicate that biomass accumulation rates may be approaching maximum levels (Fig. 9b), ecosystem carbon stocks can continue to increase for many decades as mature trees continue to sequester carbon and as dead organic matter, and soil carbon stocks continue to accumulate (Luyssaert et al., 2008). Furthermore, while past and present aging trends can inform future conditions, the applicability may be limited, because potential changes in management activities or disturbances could affect future stand age and forest growth rates (Harmon & Marks, 2002; Tepley *et al*., 2013).

The RPA assessment provides regional projections of forest carbon trends across forestland ownerships in the United States based on a new approach that uses the annual inventory to estimate carbon stocks retrospectively to 1990 and forward to 2060 (Woodall *et al.*, 2015; USDA Forest Service, 2016). The RPA reference scenario assumes forest area in the U.S. will continue to expand at current rates until 2022, when it will begin to decline due to land use change. However, national forests tend to have higher carbon densities than private lands and may have land management objectives and practices that differ from those on other lands.

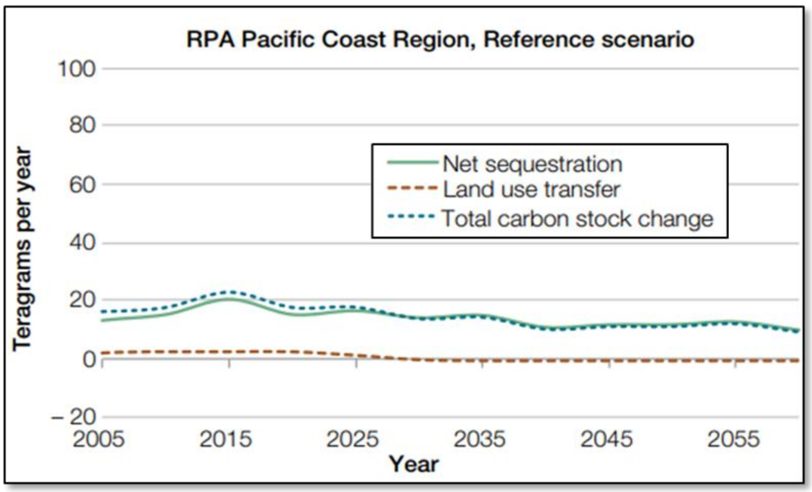


Figure 11. *Projections of forest carbon stock changes in the Pacific Coast Region (equivalent to the boundaries of Pacific Northwest Region, but includes all land tenures) for the RPA reference scenario. Net sequestration of forests is the total carbon stock change minus losses associated with land-use change.*

For RPA's Pacific Coast Region (equivalent to a combination of the Forest Service's Pacific Northwest and Pacific Southwest Region boundaries, but includes all land ownerships), projections indicate that the rate of carbon sequestration will decline gradually but will be relatively stable. The trend in total carbon stock change tracks most closely to net sequestration indicating that land-use transfers are not significant in this region (Fig. 11). At the global and national scales, changes in land use—especially the conversion of forests to non-forest land (deforestation)—have a substantial effect on carbon stocks (Pan *et al.*, 2011a; Houghton *et al.*, 2012). Converting forest land to a non-forest use removes a large amount of carbon from the forest and inhibits future carbon sequestration. National forests tend to experience low rates of land-use change, and thus, forest land area is not expected to change substantially within the Wallowa-Whitman NF in the future. Therefore, on national forest lands, the projected carbon trends may closely resemble the "net sequestration" trend in Fig. 11, which isolates the effects of forest aging, disturbance, mortality, and growth from land-use transfers and indicates a gradual decline in the rate of net carbon sequestration through 2060.

4.2 Prospective Climate and Environmental Effects

The description of forest carbon stocks and fluxes above highlights the role of disturbances, management, and environmental factors in influencing carbon dynamics on the Wallowa-Whitman NF and elsewhere across the region. However, climate change introduces additional uncertainty about how vegetation—and vegetation carbon uptake and storage—may change in the future. Climate change causes direct alterations of the local environment, including temperature and precipitation, and indirectly affects a wide range of ecosystem processes (Vose *et al.*, 2012), including vegetation growth, regeneration, and mortality. Because disturbance regimes are projected to increase with climate change (Vose *et al.*, 2018), understanding past trends is not sufficient to fully understand vegetation carbon dynamics in the future.

A climate change vulnerability assessment for a region including Wallowa-Whitman National Forest indicates that temperature is projected to increase throughout the 21st century (Halofsky et al 2019). For the period 2041-2070, mean annual temperature across the Pacific Northwest is projected to warm by 1.1 ^{o}C to 4.7 ^{o}C (Halofsky *et al.*, 2017). By the end of the 21st century in the Blue Mountains region (which includes the forest), annual temperature is projected to increase by 3.2–6.3 ^{o}C, depending on future greenhouse gas emissions. Temperature is projected to increase in all seasons, with the largest temperature increase during summer (Halofsky *et al*., 2017). Temperature is projected to increase in all seasons, with the largest temperature increase during summer (Mote et al. 2014). The frequency of summer days with extreme heat is likely to increase.

Higher temperatures will increase the length of the growing season. A longer growing season may enhance vegetation growth and carbon sequestration, particularly where water supply is adequate and temperatures are not excessive (e.g., at higher elevations) (Vose *et al.*, 2018). However, elevated temperatures will also increase evapotranspiration, resulting in increased soil respiration and reduced soil moisture. Thus, higher temperatures may negatively affect growth rates and carbon accumulation (Melillo *et al.*, 2017), particularly in water-limited vegetation at lower elevations.

Projections for mean annual precipitation in the Pacific Northwest range from −4.7% to +13.5%, averaging about +3% among models (Mote *et al.*, 2014). However, projections for precipitation are much more uncertain than those for temperature. Many global climate models project decreases in summer precipitation in the region (Easterling *et al.*, 2017). Precipitation extremes (i.e., high precipitation days and consecutive dry days) are projected to increase in frequency and intensity across the United States (Easterling *et al.*, 2017). Snowfall is projected to decrease in the region, particularly in relatively warm locations (i.e., elevations below 6,000 ft.) (Klos *et al.*, 2014, Luce *et al.*, 2014).

The combination of higher temperature, lower snowpack, and more consecutive dry days related to climate change will likely lead to lower soil moisture and greater drought stress (Wehner *et al.*, 2017). These effects will be more pronounced at middle and lower elevations in the Pacific Northwest. Drought stress may negatively affect plant productivity and carbon uptake and storage and increase effects of other stressors. For example, drought-stressed vegetation is more susceptible to insect outbreaks (Logan and Powell 2009), which can significantly reduce carbon uptake (Kurz *et al.*, 2008). Drought is also associated with increased wildfire area burned in the western United States (McKenzie and Littell, 2017). The area burned by wildfires (McKenzie *et* *al.*, 2004; Kitzberger e*t al.*, 2017) and the potential for very large fires (>12,000 acres) (Davis *et al.*, 2017) are projected to increase in the Pacific Northwest in a warming climate. These disturbances may decrease forest carbon stocks in the future.

Climate change and associated stressors are likely to lead to changes in the distribution and abundance of forest vegetation, particularly by the end of the 21st century. For example, lower-elevation species may increase in abundance at the lower end of the subalpine zone with warming temperatures and lower snowpack in the Pacific Northwest (Kerns et al. 2017, Hudec et al. 2019, Case et al. 2019). More drought- and fire-tolerant species, such as Douglas-fir, ponderosa pine, and western larch, will likely increase in abundance. Species that are less tolerant of drought and fire, such as western hemlock and Engelmann spruce, will likely decrease in abundance (Halofsky *et al.*, 2020). These changes in species and abundance can also influence carbon storage.

Vegetation shifts are most likely to occur after disturbance. For example, drought stress may preclude the establishment of tree species after high-severity disturbance, allowing dominance by non-forest vegetation (e.g., grasses and shrubs) (Halofsky *et al.*, 2020). Establishment of non-native and invasive species, such as cheatgrass, may also increase after disturbance (Hellman *et al.*, 2008). Invasive species establishment can shift the dominance of vegetation (e.g., from perennial shrubs to annual grasses) and alter the fire regime by changing fuels (Balch *et al.*, 2013). These and other vegetation type shifts could alter the long-term carbon storage in some ecosystems.

Carbon dioxide emissions are projected to increase through 2100 under even the most conservative emission scenarios (IPCC, 2014). Several models, including the InTEC model (Figure 10), project future increases in forest productivity when CO_2 fertilization is included in modeling (Zhang *et al.*, 2012). However, the effect of increasing levels of atmospheric CO_2 on forest productivity is likely to be transient and can be limited by the availability of nitrogen and other nutrients (Norby *et al.*, 2010). Thus, increases in plant productivity under elevated CO_2 could be offset by losses from climate-related stress or disturbance.

Given the complex interactions among forest ecosystem processes, disturbance regimes, climate, and nutrients, it is difficult to project how forests and carbon trends will respond under novel future conditions. The effects of future conditions on forest carbon dynamics may change over time. For example, as climate change persists for several decades, critical thresholds may be exceeded, causing unanticipated responses to some variables like increasing temperature and CO_2 concentrations. The effects of changing conditions will almost certainly vary by species and vegetation type. Some factors may enhance vegetation growth and carbon uptake, whereas others may hinder the ability of vegetation to store carbon.

5.0 Summary

Forests in the Wallowa-Whitman NF are likely maintaining stable carbon stocks. Forest carbon stocks increased by about 12 percent between 1990 and 2013. Negative impacts on carbon stocks caused by disturbances and environmental conditions have been modest and exceeded by forest growth. According to satellite imagery, fire and timber harvesting have been the most prevalent disturbances detected on the Forest since 1990. However, harvests during this period have been relatively small and low intensity. Forest carbon losses associated with harvests have been small compared to the total amount of carbon stored in the forest, resulting in a loss of about 2.3 percent of non-soil carbon from 1990 to 2011. These estimates represent an upper bound because they do not account for continued storage of harvested carbon in wood products or the effect of substitution. Carbon storage in HWPs sourced from national forests increased since the early 1900s. Recent declines in timber harvesting have slowed the rate of carbon accumulation in the product sector.

The biggest influence on current carbon dynamics on the Wallowa-Whitman NF is the legacy of intensive timber harvesting and shifting fire regimes during the 20th century. However, many stands on the Wallowa-Whitman NF are currently middle aged or older. The rate of carbon uptake and sequestration generally decline as forests age. Accordingly, projections from the RPA assessment indicate a potential age-related decline in forest carbon stocks in the Pacific Northwest Region (all land ownerships) beginning in the 2020s. According to the historical analysis of carbon accumulation in the Wallowa-Whitman NF, this decline may have already begun (Fig. 10).

Climate and environmental factors, including elevated atmospheric CO_2 and nitrogen deposition, may have also influenced carbon accumulation on the Wallowa-Whitman NF. Recent warmer temperatures and precipitation variability may have stressed forests, causing climate to have a negative impact on carbon accumulation in the mid-1980s. Conversely, increased atmospheric CO_2 and nitrogen deposition may have enhanced growth rates and helped to counteract ecosystem carbon losses due to historical disturbances, aging, and climate.

The effects of future climate conditions are complex and remain uncertain. However, under changing climate and environmental conditions, forests of the Wallowa-Whitman NF may be increasingly vulnerable to a variety of stressors. These potentially negative effects might be balanced somewhat by the positive effects of longer growing season, greater precipitation, and elevated atmospheric CO_2 concentrations. However, it is difficult to judge how these factors and their interactions will affect future carbon dynamics on the Wallowa-Whitman NF.

Forested area on the Wallowa-Whitman NF will be maintained as forest in the foreseeable future, which will allow for a continuation of carbon uptake and storage over the long term. Across the broader region, land conversion for development on private ownerships is a concern and this activity can cause substantial carbon losses (FAOSTAT, 2013; USDA Forest Service, 2016). The Wallowa-WhitmanNF will continue to have an important role in maintaining carbon stocks, regionally and nationally, for decades to come.

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